3D-seismic imagery of deeply buried iceberg ploughmarks in North Sea sediments

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Where the keels of icebergs and sea ice touch the seafloor, deformation and reworking of the sedimentary substrate may take place. Point impacts roduce pits in the seafloor, whereas continuing ice drift results in the formation of linear to curvilinear depressions referred to as ploughmarks, urrows or scours (Woodworth-Lynas et al. 1991). Sea-ice keels only exceptionally exceed about 20 m below water, where pressure-ridging takes lace. By contrast, the keels of icebergs can range from tens of metres for small irregular bergs produced from grounded tidewater glaciers, to over 00 m where calving takes place from major ice-sheet outlet glaciers (Barnes and Lien 1988; Dowdeswell et al. 1993; Dowdeswell & Bamber 2007). he presence of large iceberg ploughmarks in the geological record therefore indicates that ice was present at sea-level to release bergs into the djacent ocean waters. 3-dimensional (3D) seismic data are required, however, in order to identify these features on buried shelf surfaces (Fig. 1).

escription

Two 3D-seismic cubes from the central North Sea Basin (57°N 2°E) were examined (Dowdeswell & Ottesen 2013), as part of a wider study of the edimentary architecture and basin-fill of the North Sea during the past 2.7 million years (Ottesen et al. 2014). The cubes were C08 (62 by 50 km and ,100 km^2) and E08 (less regular in shape and 1,900 km^2) of the Petroleum Geo-Services (PGS) North Sea MegaSurvey (Fig. 1f). The cubes had a ickness of Quaternary sediments of between 600 and 900 m, calculated using a sound-velocity varying between 1850 and 1900 m s^{-1} across the ubes. A series of clinoforms, indicating the presence of palaeo-shelves in the Early Quaternary seismo-stratigraphic record of the central North Sea, s shown in Figure 1e. The Base Naust-equivalent reflection represents the base of the glacier-influenced sedimentary package. Examination for the resence of linear and curvilinear features on buried surfaces within the cubes took place through analysis of horizontal time slices by stepping down rom the seafloor every 10 ms through each cube (Dowdeswell & Ottesen 2013).

Linear to curvilinear features, often distributed in a chaotic pattern, were observed between about 270 and 900 ms within the Early Quaternary ediments of the two 3D cubes in the central North Sea (Fig. 1a-d). The mean width of the features was approximately 50-60 m and average length f about 3 km. The features are depressions, typically a few metres deep relative to the general level of the palaeo-shelf surface in which they appear. hey are sometimes fringed by berms on one or both sides (Fig. 1b). Abrupt shifts in feature orientation are sometimes observed, occasionally ccompanied by the occurrence of rounded pits a few tens of metres in diameter (Fig. 1d).

nterpretation

The buried linear to curvilinear depressions are very similar in morphology to seafloor landforms interpreted to be produced by the ploughing ction of iceberg keels through soft sediments in both bathymetric and earlier side-scan sonar imagery of modern high-latitude shelves (e.g. Barnes & Lien 1988; Dowdeswell et al. 1993; Dowdeswell et al. 2010). The icebergs producing these Early Quaternary ploughmarks are thought to be erived from a full-glacial Scandinavian Ice Sheet to the north (Ottesen et al. 2014). Similar buried landforms, also interpreted as iceberg loughmarks, have been identified in, for example, the Dutch sector further south in the North Sea (Kuhlmann & Wong 2008).

The identification of iceberg ploughmarks buried beneath hundreds of metres of Quaternary sediments in the central North Sea Basin is only ossible where 3D seismic data are available. Even relatively dense 2D seismic grids are usually insufficient to allow the recognition of these often haotically distributed sets of landforms.

The occurrence of iceberg ploughmarks buried deep within the Quaternary sedimentary record is a clear indicator of the presence of ice sheets to ea level. In the same way that iceberg-rafted debris found within fine-grained marine sediments in ocean basins has been used as an indicator of the nception of an Ice Age (e.g. Jansen & Sjøholm 1991), the presence of iceberg ploughmarks can be used to infer the start of a glacial period in the arth's past record (Dowdeswell et al. 2007). The long-term preservation of ploughmarks in the kilometre or so of Quaternary sediments often resent on high-latitude continental margins requires, however, that former continental shelves are preserved within the geological record, rather than eing eroded by advancing ice sheets during the successive glacial-interglacial cycles that make up a whole Ice Age.

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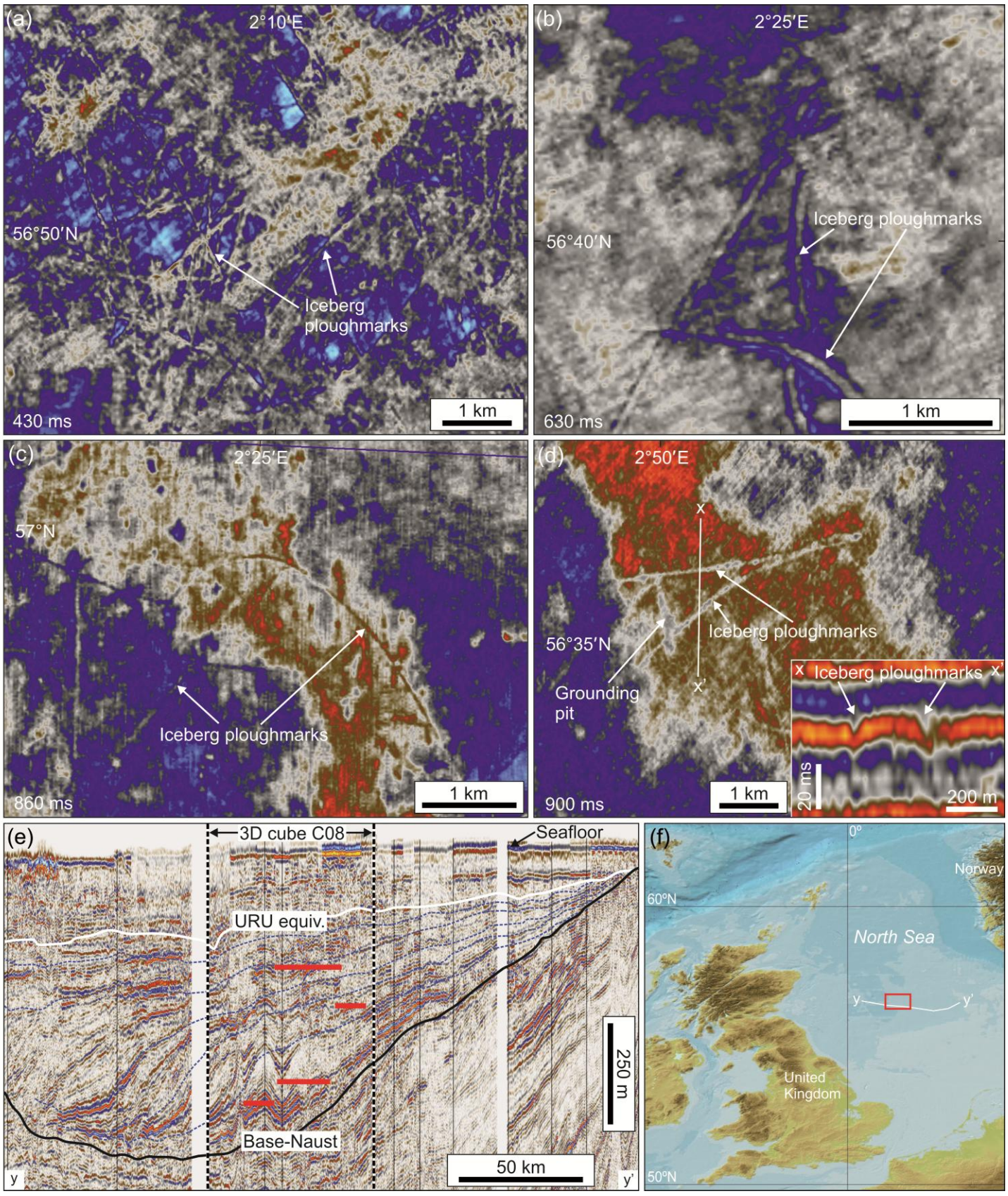
'ig. 1. (a), (b), (c) and (d) Iceberg ploughmarks in 3D-seismic cube C08 from the central North Sea Basin. The iceberg ploughmarks are shown in our different time slices: (a) 430 ms, (b) 630 ms, (c) 860 ms, (d) 900 ms, with the inset showing two ploughmarks in cross-section. (e) Composite eismic profile through 3D-seismic cube C08, showing the Quaternary seismic stratigraphy of the central North Sea Basin above the Base-Naust eflection (Ottesen et al. 2014). VE x 140. The Upper Regional Unconformity (URU) equivalent (white line) and Base-Naust (black line) horizons nark the stratigraphic boundaries of the Early Quaternary (Ottesen et al. 2014). Dashed blue lines are other major reflections. Red lines are locations f time slices from which the iceberg ploughmarks in (a), (b), (c) and (d) are identified. (f) Location of the study area in the North Sea (red box is D-seismic cube; white line is seismic profile; map from IBCAO v. 3.0).


(a)
2°10′E
56°50′N
Iceberg ploughmarks
1 km
430 ms
(b)
2°25′E
Iceberg ploughmarks
56°40′N
1 km
630 ms
(c)
2°25′E
57°N
Iceberg ploughmarks
1 km
860 ms
(d)
2°50′E
x
x'
56°35′N
Iceberg ploughmarks
Grounding pit
1 km
900 ms
x
Iceberg ploughmarks
x'
20 ms
200 m
(e)
3D cube C08
Seafloor
URU equiv.
Base-Naust
250 m
50 km
y
y'
(f)
0°
60°N
Norway
North Sea
y
y'
United Kingdom
50°N